

# **Prediction of the Low Frequency Wave Field on Open Coastal Beaches**

H. Tuba Özkan-Haller

College of Oceanic and Atmospheric Sciences

Oregon State University

104 Ocean Admin Bldg

Corvallis, OR 97331-5503

phone: (541) 737-9170 fax: (541) 737-2064 email: [ozkan@coas.oregonstate.edu](mailto:ozkan@coas.oregonstate.edu)

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<http://ozkan.coas.oregonstate.edu>

## **LONG-TERM GOALS**

The long-term goal of this study is to arrive at a predictive understanding of the time varying circulation in the nearshore region given only information about the incident wave field and bottom bathymetry. Predictions should include information about the kinematics of low frequency motions (their wavenumbers and frequencies) as well as information about their dynamics (energetics).

## **OBJECTIVES**

The scientific objectives of the study are related to gaining an understanding of the important features of the nearshore circulation field, so that quantitative predictions about the circulation field at a given site can be reliably made. Specific objectives include: 1. The assessment of the impact of specific features of wave groups on edge wave development and the prediction of the finite amplitude edge wave field resulting from a balance between the wave group forcing and dissipation mechanisms. 2. The assessment of the degree to which non-uniformities in the bottom bathymetry (both abrupt and gradual) affect the resulting low frequency wave climate. 3. The assessment of the importance of interactions between different modes of time-varying motions in the nearshore region, as well as interactions between these modes and the incident wave field. 4. To arrive at a predictive understanding of low frequency motions.

## **APPROACH**

The approach is to use a numerical model to assess our understanding of time-varying circulation in the nearshore region. The finite amplitude behavior of low frequency motions in the nearshore region is a function of a balance between processes that generate these motions and processes that dissipate them. The approach used here is to isolate several generation, dissipation processes as well as processes affecting the evolution of the motions in a modeling effort and start with the simplest possible theory to model the processes. More complicated and full treatments are introduced in a step-by-step fashion resulting in an understanding of the effects of the processes and their parameterizations on the resulting circulation field.

We are utilizing a model that solves the time-dependent shallow water equations with additional terms to account for the effects of forcing and damping (Özkan-Haller and Kirby, 1997). Although only valid in shallow water, these equations can model the leading order behavior of both low frequency gravity

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motions (edge waves) and vorticity motions (shear waves). Eight partial differential equations are solved simultaneously to obtain the evolution of eight unknowns; namely, the phase-averaged water surface elevation, the phase-averaged cross-shore and longshore velocities, the horizontal shoreline runup due to low frequency motions, the incident wave energy, the incident wave wavenumber, the local incident wave direction, and the water depth. The effects of bottom friction, turbulent momentum mixing, incident wave transformation and forcing, wave-current interaction and arbitrary bottom movement, are included in a rudimentary fashion. We begin our modeling effort by generating edge waves and shear waves in idealized conditions, and progressively move to more realistic situations where these motions are allowed to coexist and interact.

## WORK COMPLETED

We have completed the implementation of an equation governing the behavior of the time-varying incident wave energy in order to simulate the evolution of incoming wave groups. We subsequently analyzed the generation of edge waves by a bi-chromatic wave field, including the effects of nonlinear wave interactions as well as the effect of a moving breakpoint (Lippmann *et al.*, 1997). We successfully generated various edge wave modes of finite amplitude and have isolated the effects of nonlinear generation mechanisms and generation due to a moving breakpoint. Also under investigation was the half-life of the generated waves. A finding suggested that finite amplitude edge waves can exist in both a high forcing-high dissipation environment as well as a low forcing-low dissipation environment. We have analyzed measurements obtained previously on a pocket beach to gain information about the dissipational climate in which edge waves may exist.

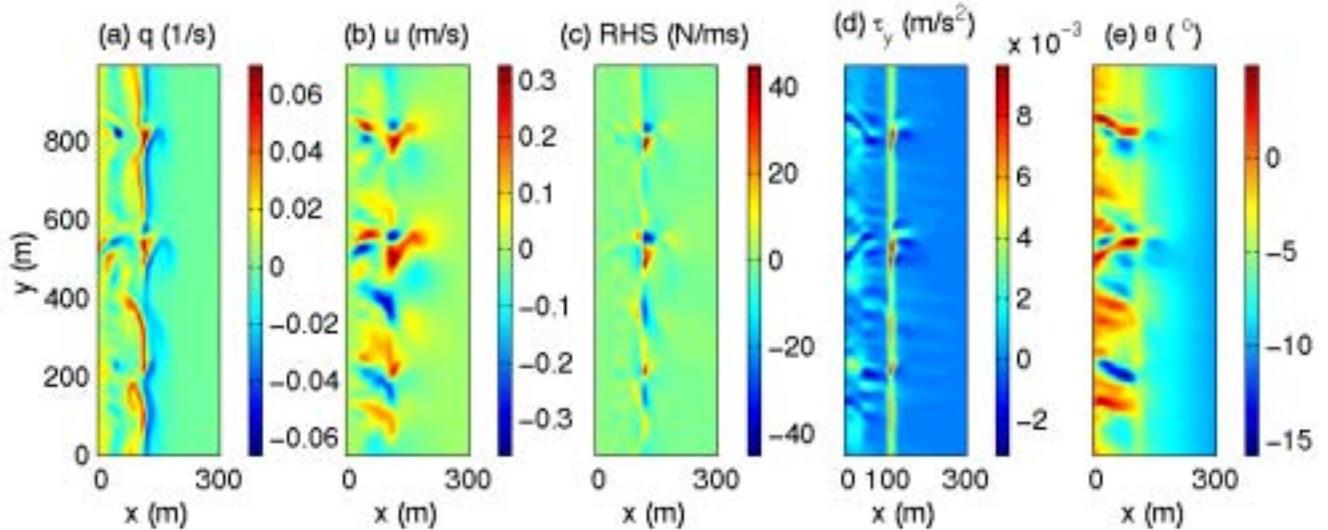
We have completed the implementation of the time dependent equations that approximate the behavior of phase-averaged properties of the incident waves; namely, the incident wave energy, the wavenumber and the local angle of incidence. The energy equation for the incident waves is used to model the former while the conservation of wavenumber principle is introduced to model the latter two variables. These model equations include effects of the current velocities. In this manner the forcing of wave-induced currents is modeled while taking the effects of the generated currents on the wave field into account. We have analyzed wave-current interaction effects in environments with varying amounts of dissipation due to bottom friction. We concentrated on the flow properties of the resulting currents as well as propagation speeds of the resulting motions. Also of interest was the effect on the shoreline runup.

We are currently working on an analytical model to isolate unstable behavior in the surf zone due to the interaction of unsteady currents and the incident wave field. Utilizing this linear instability model we are searching for unstable behavior in a system that includes unsteady currents as well as an unsteady wave field due to the effects of the currents on the incident waves.

## RESULTS

During our investigation of the effect of wave-current interaction on finite amplitude shear instabilities of the longshore current, we found that the offshore extent of the resulting motions is limited significantly by the presence of wave-current interaction, so that the signature of the instabilities offshore of the surf zone is limited. On the other hand, we found that this signature is significantly more pronounced within the shoreline runup when wave-current interaction is considered (Figure 1(a)). Analyzing the wave-current interaction terms within the energy equation for the wave motion

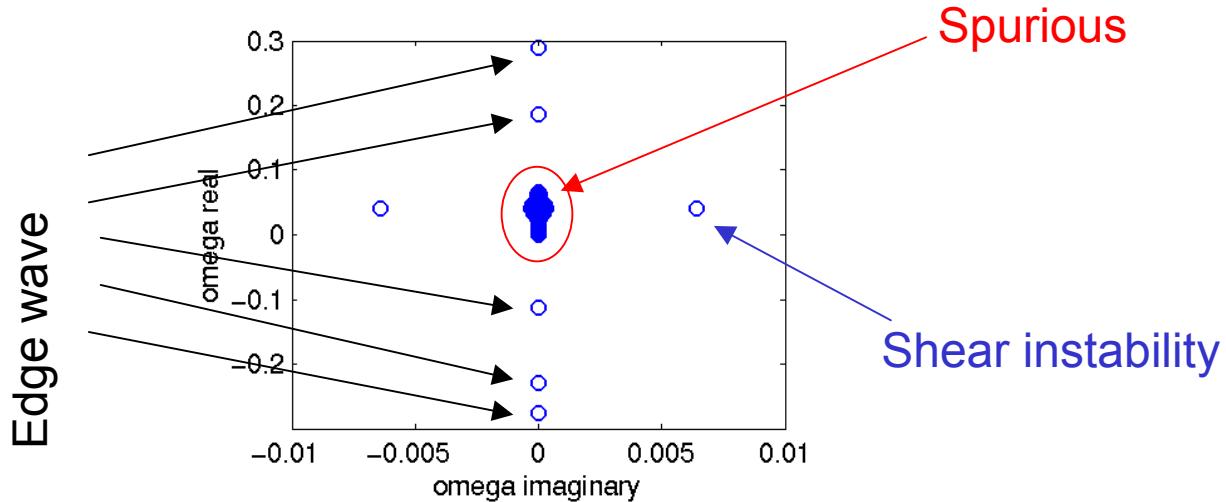
(Figure 1(c)) we found that in areas where the currents oppose the waves (see Figure 1(b)), the wave field gains energy due to work done by the circulation on the waves. In areas where the circulation is co-linear with the wave propagation direction, the opposite occurs. This effect introduces an asymmetry causing the offshore extent of the resulting circulation to be limited. Also, any offshore directed jets that are generated due to the finite amplitude shear instabilities cause the wave field to refract around them. The effect of the refraction causes variations in the wave angle of incidence near the shore (Figure 1(e)) setting up a variation in the longshore current forcing near the shoreline (Figure 1(d)). Our simulations thus suggest that the enhanced fluctuations near the shoreline are the result of a forced circulation pattern that is set up shoreward of any localized cross-shore features in the circulation in mid-surf zone (see Özkan-Haller and Li, 2002).



**Figure 1: Snapshots for a circulation field involving the instability of a longshore current that flows in the +y-direction. Depicted are (a) the vorticity, (b) the cross-shore velocity, (c) the wave-current interaction terms within the energy equation for the wave motion (see Özkan-Haller and Li, 2002), (d) longshore component of the wave forcing, and (e) local angle of wave incidence, where x points offshore and y points alongshore. Of note are areas where the current field performs work on the wave field, causing it to gain energy (red areas in panel (c)). Note that these coincide with offshore directed flow features (panel (b)). These also cause refraction of the incident wave field (panel (e)), which, in turn, cause variations in the wave forcing of the circulation (panel (d)), ultimately leading to strong fluctuations in the velocities near the shoreline, which are absent when wave-current interaction is neglected.**

Our simulations on the nonlinear evolution of shear instabilities of the longshore current also suggest that the onset of the instability is delayed when wave-current interaction is taken into account (see Özkan-Haller and Li, 2002). This finding suggests that the initial linear growth rate of the instability is reduced by the presence of wave-current interaction. A way to isolate the mechanism by which this occurs is to carry out a linear instability analysis of the system of seven equations that form the basis for the nonlinear model that was utilized. We start by analyzing the linear instability of a simplified system of equations assuming wave-current interaction can be neglected and the low frequency motions are neither actively forced nor dissipated. In this case, the linear instability analysis gives

information about both the gravity and the vorticity modes that exist as solutions to this system. The instability analysis assumes that the frequency of the solutions can be a complex number, where a positive complex part indicates initially exponentially growing modes such as shear instabilities of the longshore current. Neutrally stable modes such as edge waves will be characterized by a zero imaginary frequency component. Figure 2 shows the resulting eigenvalues for a wavelength of  $\sim 105$  m for a situation involving a plane beach and a peak longshore current speed of about 1 m/s. In this case, the linear instability analysis gives rise to several edge wave modes along with a shear instability mode (marked in Figure 2). Also evident is the presence of a number of spurious modes near the origin. These modes are generated either due to rapidly varying solutions that are not adequately resolved by the discretization (such as incident gravity waves) or by a continuum of physical solutions that can not be expressed within a discretized model. The occurrence of such spurious modes in the solution of linear instability problems is commonly cited in the literature and methods to isolate them from true physical solutions exist. We isolate spurious modes by carrying out a convergence analysis and utilizing the reciprocal eigenvalue drift ratio as suggested by Boyd (2001).



**Figure 2: Real part of the radial frequency versus the imaginary part of the radial frequency for motions at radial wavenumber  $k=0.06$  rad/m. Positive imaginary frequencies indicate an exponentially growing mode, negative imaginary frequencies indicate exponentially decaying modes. The edge wave modes, shear instability modes, and spurious modes are marked.**

The inclusion of frictional damping modifies Figure 2 by introducing a negative imaginary component to each mode indicating a tendency for exponential decay in time. The inclusion of forcing due to alongshore wave height modulation introduces positive imaginary components indicating growth of motions at the same time scale as the wave height variations. At this step, wave-current interaction is also included leading to the possibility that a mode may grow due to a positive feedback between the groupy wave motions and the resulting low frequency response. Our preliminary results including wave-current interaction confirm that the growth rate of the instabilities is slowed due work done by the circulation on the waves.

## IMPACT/APPLICATIONS

This study sheds light on the processes that are important in the low frequency range of the energy spectrum, such as interactions between low frequency waves and response of the low frequency environment to external forcing. This study can also serve as a benchmark for other studies that do not explicitly resolve the time-varying low frequency wave field but instead focus only on the mean circulation. Results obtained here should also be relevant to studies that are not restricted to low frequency motions, but where the low frequency motions are embedded in higher frequency oscillations, making the processes difficult to identify.

## TRANSITIONS

The work on the project will lead to a robust modeling tool which is capable of predicting the time-varying circulation field including effects such as incident wave forcing, bottom friction, momentum mixing and wave-current interaction. The model code is available to the engineering and science communities.

## RELATED PROJECTS

The effect of edge waves and shear waves on the evolution of bathymetry is being investigated as part of the ongoing NOPP project (Lead P.I. J.T. Kirby) “Development and Verification of a Comprehensive Community Model for Physical Processes in the Nearshore Ocean”. A version of the code developed here is utilized in the project “Modeling Beach Morphology Changes Coupled to Incident Wave Climate and Low Frequency Currents” (P.I. J.T. Kirby). Aspects of unsteady currents in the nearshore zone are the topic of the study “Nonlinear Time-Dependent Currents in the Surfzone” (P.I. D. Slinn).

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